

Metrology in Mask Manufacturing

A major source of registration failure in microlithography was found to be due to variations in optical field sizes defined by the dies, caused by unsatisfactory focus control. Two methods for determining variations in optical field sizes are described. Both allow measurements of selected registration errors with an uncertainty of $\pm 0.01 \mu\text{m}$ (1σ) under manufacturing conditions using commercially available measuring microscopes. The long-term registration stability of stepped-mask exposure systems was also investigated. It is concluded that maintenance of registration over long periods of time can be improved through accurate focus control along the optical axis. Finally, it is suggested that no single set of measurements at one point in time can completely characterize a microlithographic system. Periodic monitoring of key measurable parameters during use is advisable.

Introduction

The revolutionary development in semiconductor electronics during the last twenty-five years is unique in the history of technical evolution. This development was made possible by the combination of a number of advanced but unrelated technological fields. One such field, microlithography, played a major role in the high-volume production of multiple-pattern arrays.

The manufacture of large-scale integrated circuits (IC) begins with the computer-aided design of the circuit elements. The complex design structure of the resulting IC die is converted into a set of (5 to 15) $10\times$ reticle masks, using either optical- or electron-beam pattern generators. Then, each of these $10\times$ reticles is reduced into a $1\times$ mask by step-and-repeat exposures, thus ensuring both microminaturization and high-volume production. The $1\times$ mask arrays of stepped fields are subsequently transferred by 1:1 exposure in similar arrays on the wafer, with each mask defining a selective transfer process of special materials into or onto the wafer. A critical condition for satisfactory performance of the IC chips is the registration accuracy of the masks.

Registration (or overlay) is defined as the exact alignment of associated patterns of overlaid pattern arrays. Registration is easily defined, but errors in registration are difficult to measure and analyze because of the number of variables and

parameters involved. In this paper we address variations in the $1\times$ die fields. To appreciate the stringent metrological requirements, one must remember that the patterns we deal with are on the order of $2 \mu\text{m}$ and the diameters of the pattern arrays are on the order of 100 mm, that their fabrication involves different types of complex equipment, and that the production cycle for ICs may take anywhere from several weeks to several months. The last point demonstrates the need for long-term stability of the various systems and processes used.

With decreasing dimensions in circuit elements and increasing die sizes and wafer diameters, the registration tolerances must also decrease proportionally. As an extreme case, lines smaller than $0.1 \mu\text{m}$ have been reported in use [1]. However, even if such lines and basic patterns of similar sizes could be made uniform enough over large arrays of fields in a cost-effective production environment, the registration requirements between different layers would be quite formidable and probably not realizable for many years to come. One of the principal reasons for this difficulty is that the metrological aspects of microlithography must be controlled to a degree which is impossible at present.

To prepare for such demanding requirements, product inspection and/or equipment monitoring would have to be

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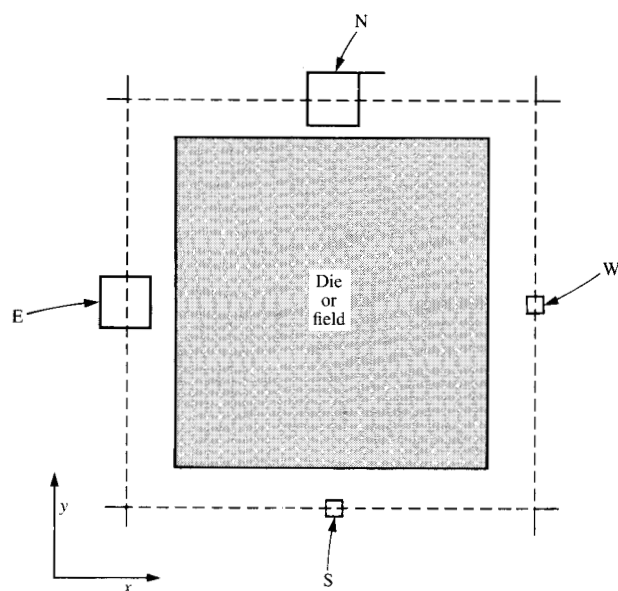


Figure 1 Layout of four square-shaped test patterns, N, S, E, and W, surrounding a single $1 \times$ field. The design center of the squares determines the stepping periodicity for the corresponding axes.

designed to permit measurements of better than $0.005 \mu\text{m}$. Questions spring up immediately concerning how accurately measurements can be made in a manufacturing environment, and how one goes about making measurements which will permit analysis of *individual* overlay-related variables of the microlithographic equipment as a first step to achieving such improvement. Furthermore, it is important to ascertain the long-range stability of the systems by monitoring and (partial) averaging measurements over long periods of time to get a feel for what we are up against. Of course this can only be done if the measurement process itself remains virtually unchanged over time.

Laser-controlled lithographic mask stepping systems reportedly perform exceptionally well. For instance, random stepping errors smaller than $\pm 0.02 \mu\text{m}$ (1σ) have been found [2]. It therefore appears reasonable to demand that the measurement uncertainty likewise should not exceed $\pm 0.02 \mu\text{m}$. Such requirements presently cannot be achieved with any known two-dimensional measurement system for long distances (150 mm) and over long periods of time (several weeks). The earlier paper [2] introduced a method for self-measurement of lithographic pattern arrays. A variety of individual mask registration errors, some smaller than $\pm 0.05 \mu\text{m}$, could be determined with this method. Consequently, inexpensive and simple characterization and monitoring of the performance of lithographic equipment became feasible with a previously unforeseen accuracy. That study also led to the installation of deflection-free mask clamping means

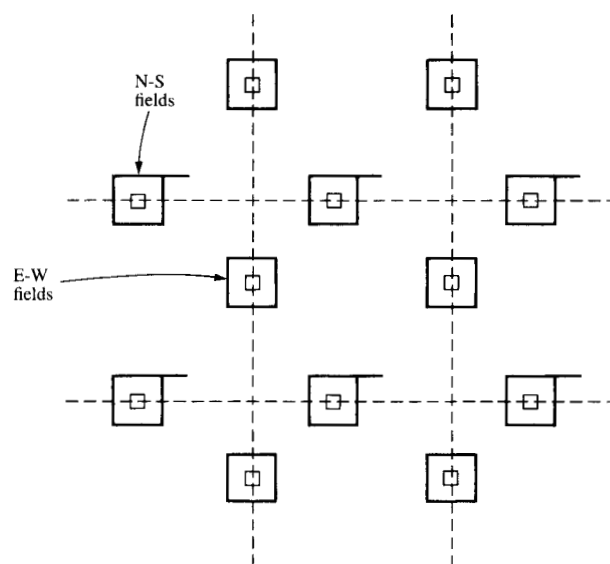


Figure 2 The appearance of the interlaced patterns (N-S and E-W) is shown after stepping for several adjacent fields. The bars attached to the large N-S squares simplify identification for measurement purposes.

which eliminated array distortions due to non-controllable mask deformations. However, some unexpected variations in registration still remained, especially in larger die sizes.

This paper addresses field-related registration errors of product (and test) masks and concludes with some problems needing further investigation.

Inspection of product masks

The increasingly stringent demands of integrated circuit fabrication require inspection of array patterns at critical points in the production cycle in order to ensure maximum yields when these arrays are superimposed on the wafer at later points in time. This paper deals with single pattern arrays (masks) which play a major, and critical, role in today's semiconductor technology; but it is also applicable to wafer-exposure systems (especially mask steppers). Two methods of measurement are described: the first is for use by manufacturing engineers to measure registration to within $\pm 0.03 \mu\text{m}$ (3σ); the second is designed for long-term system monitoring. The results indicate the presence of a type of registration error which until now appears to have received little if any attention and which seems to affect all optical lithographic systems to a greater or lesser degree.

The exact determination of field-related registration errors can be achieved with a line width measurement microscope [3a]. For this purpose the peripheral regions of $10 \times$ product reticles should contain two or more sets of

special patterns. Each set consists of two concentric structures which are located in the extreme opposite regions of the reticular field (Fig. 1). At $1\times$, the center-to-center distances between the peripheral patterns are equal to the corresponding stepping periodicities. Hence, a stepped mask displays the associated patterns in an interlaced fashion (see Fig. 2), thus facilitating the determination of both linear changes in size and rotational changes of fields by performing linear measurements. Figure 3 is a blow-up of two pattern pairs indicating the four variables which determine the degree of registration error and bias of both interlaced patterns in the x -axis and y -axis of the $1\times$ mask coordinate system. Each center-to-center error is determined from two measurements as follows:

$$1/2(x_1 - x_2) = X_1;$$

$$1/2(y_1 - y_2) = Y_1;$$

$$1/2(x_3 - x_4) = X_2; \text{ and}$$

$$1/2(y_3 - y_4) = Y_2.$$

The bias values generally differ from zero (even for a well-adjusted system); consequently, the interlaced squares (in Fig. 3) are generally not concentric, *i.e.*, the $X_1, \dots, Y_2$ averages are not equal to zero either. The relationships between the variables X_1, X_2, Y_1, Y_2 and the registration variables and biases are given in Table 1. This table illustrates some of the complexities of photolithographic registration. The changes which affect the four target sites per field (Fig. 1) can be divided into systematic and random errors. Systematic errors enter the variables $X_1, \dots, Y_2$ from distortions due to lens design and various degrees of camera misalignment. Systematic errors of the rotational type (Y_1 and X_2) are also introduced by the built-in lack of parallelism of the $10\times$ and $1\times$ coordinate axes and minute deviations from orthogonality of the $10\times$ pattern generators.

Random errors are introduced from independent registration tolerances and alignment biases of the $10\times$ reticles. These in turn can be caused by (1) pattern generators, (2) contact printing of the $10\times$ high-resolution emulsion mask into a chrome mask (*e.g.*, due to plate-to-plate bending caused by surface waviness), (3) operator misalignment, or (4) minute rotational changes of the $10\times$ reticle support structure over time. Random stepping errors can also be added to each of these factors. However, these can generally be neglected due to the accuracy of interferometer-controlled stepping tables and the effect of averaging measurements over several fields. Additional variables can be derived by comparing results from selected fields, from different masks, and from long-term monitoring data.

Automatic line width measurement microscopes with excellent performance characteristics became available com-

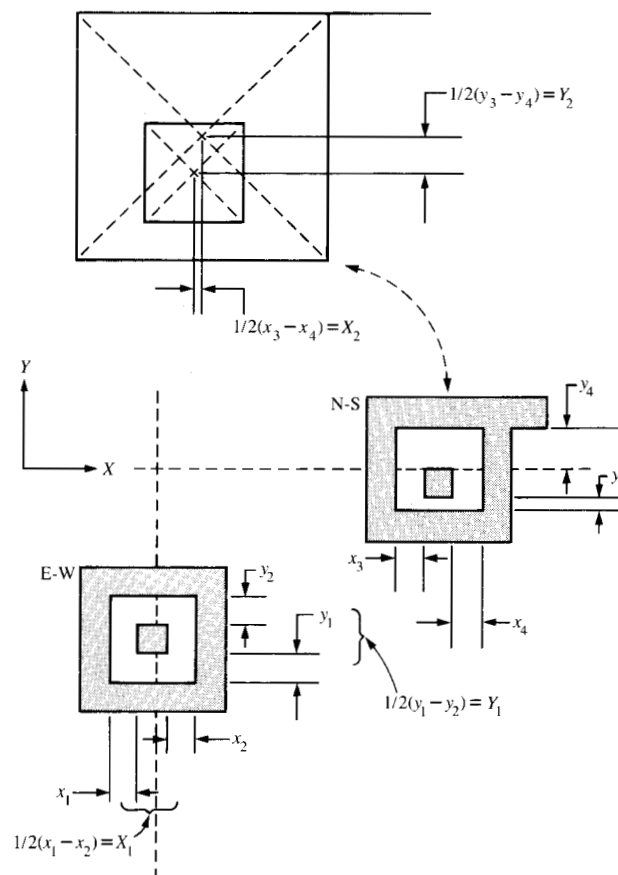


Figure 3 The variables $x_1, \dots, x_4$ designate the measurements to be performed. From these, the center-to-center distances between the interlaced squares $X_1, \dots, Y_2$ are calculated.

Table 1 Major causes of changes in field size. Here (S) denotes a systematic error per exposure step, (R) denotes a random error between arrays, (P) denotes a partial random error, and (C) is an error due to lack of parallelism between the axes of the $10\times$ and the $1\times$ coordinate systems.

X_1 $= 1/2(x_1 - x_2)$	Y_1 $= 1/2(y_1 - y_2)$	X_2 $= 1/2(x_3 - x_4)$	Y_2 $= 1/2(y_3 - y_4)$
Lens distortion and camera adjustment (S)	$10\times$ fiducial bias (S), (C)	Same as Col. No. 2	See Col. No. 1
Δ Focus (P)	Operator alignment or skew (R)	Orthogonality error of reticle generator (S)	
$10\times$ contact printer (P)			

mercially during the late 1970s [3b]. The variable pairs (x_1, x_2) , (y_1, y_2) , (x_3, x_4) , and (y_3, y_4) can best be measured with these instruments since they measure small lines, free

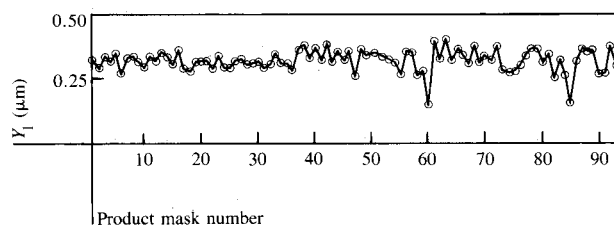


Figure 4 The die orientation Y_1 (operator alignment error) for 93 product masks remains in most cases within $\pm 0.07 \mu\text{m}$. The offset of $0.3 \mu\text{m}$ is caused by the non-parallelism of the table coordinate system at $1\times$ and the $10\times$ alignment targets.

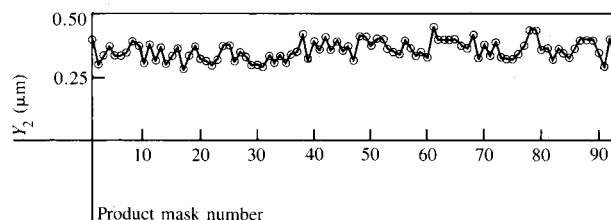


Figure 5 The total change of die sizes along the y -axis for the same set of masks never exceeded $0.08 \mu\text{m}$.

Table 2 Box-in-box measurement data. All numbers are given in units of 25 nm. All Δ -values represent deviation from average.

	X_1 $\Delta \text{Field } (x)$	Y_1 $\Delta \text{Field } (y)$	X_2 ΔSkew	Y_2 $\Delta (\text{Skew} + \text{distortion})$
A	0.5	1.5	-1.0	1.0
B	0.0	0.5	1.5	1.0
C	-1.5	-0.5	1.0	1.0
D	0.5	0.0	0.5	1.0
E	1.5	2.0	0.0	0.5
Range	3.0	2.5	2.5	0.5
mean	0.2	0.7	0.4	0.9

from human error, through automatic focus sensing and automatic threshold determination. Subsequently, the variables X_1 , Y_1 , X_2 , and Y_2 can be calculated and plotted.

To provide a representative case, it is advisable to measure at least five selected fields (denoted A, B, C, D, and E) per stepped array. Table 2 shows some typical results. These results are stored for each mask in a computer, together with related descriptive information identifying the $10\times$ artwork generator, the $1\times$ stepping system, the day code, the product identification, etc. The results are automatically averaged (to reduce the effects of random stepping and measurement

errors) and are then plotted at regular intervals. This permits assessment of the degree of registration of the relevant mask sets. A well-designed and maintained lithographic system (comprised of various types of equipment and human operators) produces plots of the type shown in Figs. 4 and 5. These display two of the variables from Table 1 over a period of many days of production. Various modes of display are feasible. The skew (Y_1) for a batch of 93 product masks is shown in Fig. 4. With only a few exceptions, the skew alignments by the system operators vary generally by no more than $\pm 0.07 \mu\text{m}$ from the average, which represents the angular bias between the $10\times$ fiducial coordinate system and the $1\times$ stage coordinate system. The measurement of the change in the $1\times$ field size in the y -axis (Y_2 , which depends on the $10\times$ chrome reticle, the uncertainty of focus during exposure, and the stepping and measurement errors) also varies only slightly from its average value, as shown in Fig. 5.

The preceding results demonstrate the behavior of a well-functioning operation which depends on many independent factors, including equipment performance, operator skill, and field size. (Note that smaller fields or dies are affected less by rotational errors or skew, since the alignment at $10\times$ always occurs at the extreme locations of the reticle). Figures 6 and 7 illustrate these points. They represent another operation and also groups of different die sizes. In this case the errors are substantially larger. In the skew error plot in Fig. 6, four different groups of masks can be clearly distinguished. Starting from the left, the first group of 17 masks exhibits an average bias (in Y_1) of about $0.6 \mu\text{m}$ and substantial fluctuations. The second group (masks 18 to 45) has an average bias of only $0.15 \mu\text{m}$; skew deviations have also decreased. The third group (masks 46 to 54) shows the least amount of operator error and is centered about $0.05 \mu\text{m}$. The last group (masks 55 to 71) is similar to the second, but its average deviation is $-0.05 \mu\text{m}$. Figure 7 shows a similar plot for the changes of field size along the y -axis of the same batch of masks. Here, only three groups can be readily recognized: masks 1 to 17, masks 18 to 45 and masks 46 to 71. These groupings correspond to those in the earlier figure, except that the last grouping in Fig. 6 is subdivided into two groups. Before discussing the causes of these variations any further, let us investigate the long-term stability of a mask stepper.

Variations of field size with time

The determination of the exact causes of changes to the field size can be simplified by separating the $10\times$ reticle errors from those introduced by the step-and-repeat system. For this purpose, a special test mask was used to monitor, on a weekly basis, the performance of the stepping system over time. The square field of the $10\times$ test plate was framed by a $25\text{-}\mu\text{m}$ -wide line and the $1\times$ stepping pitch was adjusted so

that adjacent fields were separated by about $7\text{ }\mu\text{m}$. The x - and y -spacings between adjacent fields could then be measured precisely by measuring line width, space, and line width. The center-line-to-center distance is calculated by summing the half-line width and space values.

Figure 8 shows changes in field sizes during a 16-month period of monitoring. Each point along the horizontal time axis comprises an average of about seven monitoring masks (one per week). In addition, five fields were measured (and averaged) on each mask. The four measured points per display point on the time axis represent relative measurements of the four sides of an 8.5-mm-square field. The double averaging used practically eliminates the influence of random stepping errors and measurement errors (both of which were less than $0.05\text{ }\mu\text{m}$ to begin with). The variations observed in Fig. 8 indicate that the $1\times$ field size did not remain constant in spite of the fact that the same $10\times$ reticle was used as input and the same bias for automatic focusing was used throughout the entire monitoring process.

Discussion and analysis

These results lead to a number of conclusions, some of which must be considered tentative. Let us first reiterate that the errors associated with the interferometer-controlled stepping table are smaller than $\pm 0.05\text{ }\mu\text{m}$ and can therefore be neglected. The results of Fig. 5 demonstrate that the artwork generator errors of the $10\times$ HR (high-resolution) emulsion mask can also be discarded, provided that the same generator is used for all HR masks of a set.

However, there are at least two additional types of errors which may affect the $10\times$ reticle. The first can be introduced by contact printing the HR reticle into chrome, as is frequently done to permit repair of defective patterns. This error occurs especially with inadequately designed and/or improperly maintained contact printers and can cause misregistrations ranging from $2\text{ }\mu\text{m}$ to greater than $6\text{ }\mu\text{m}$ between associated $10\times$ reticles. This type of error can be neglected for E-beam-generated $10\times$ reticles. The second $10\times$ error arises from the angular alignment tolerance (skew) of the reticle introduced by the operator. The results, as shown by the plot of variable Y_1 (Fig. 4), indicate that a skilled operator can maintain the skew of the fields (*i.e.*, the angle between the $10\times$ x -axis and the $1\times$ x -axis of the stepper) to within $\pm 0.07\text{ }\mu\text{m}$ per 8.5-mm field.

A major portion of mask misregistration was found to be due to a variation in the field size. This error affects not only product masks but also test masks, even if the same $10\times$ reticle is used. A variety of experiments were performed, subjecting the stepping apparatus to all kinds of disturbances during operation, such as tilting the entire structure slightly, defocusing, etc. The only disturbance we found which gener-

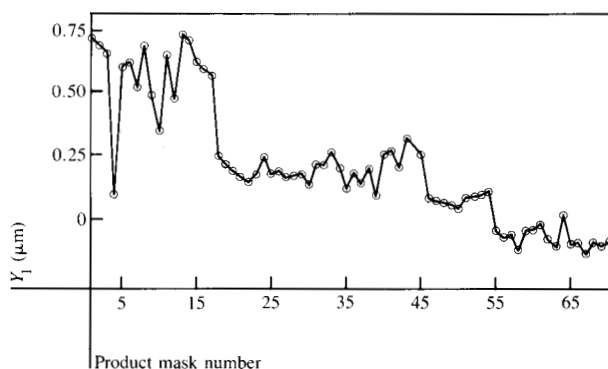


Figure 6 This group of 71 masks was affected not only by substantial variations due to faulty $10\times$ die alignment but also by changing $10\times$ offsets (*e.g.*, due to die errors or displaced reference marks), causing a maximum change of registration of about $0.8\text{ }\mu\text{m}$.

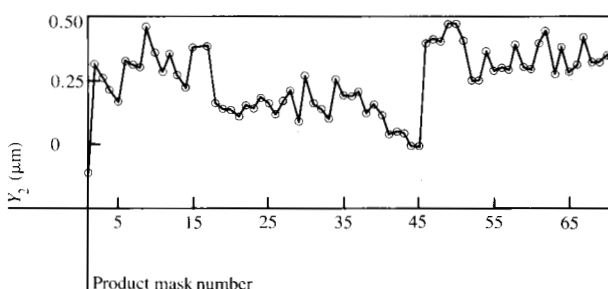


Figure 7 The 71 masks of Fig. 6 also showed substantial changes of field size, indicating, for instance, errors in dimensions of the $10\times$ die.

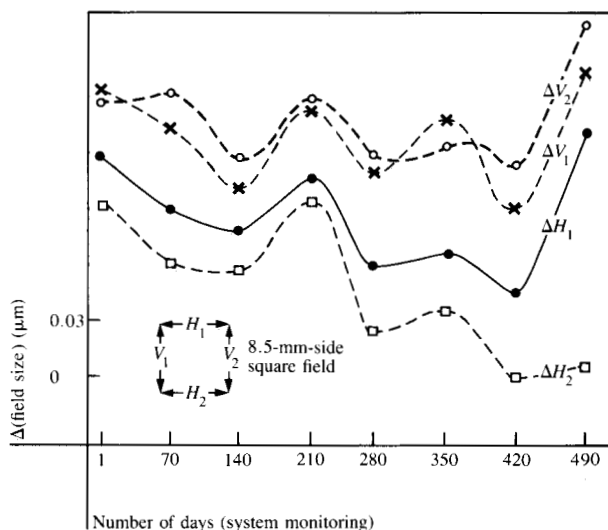


Figure 8 The four sides of a nominally square field (at $1\times$ 8.5 mm on the side) were monitored over a period of about 500 days using the same $10\times$ test reticle. The largest change ($0.25\text{ }\mu\text{m}$) was found for the side H_2 .

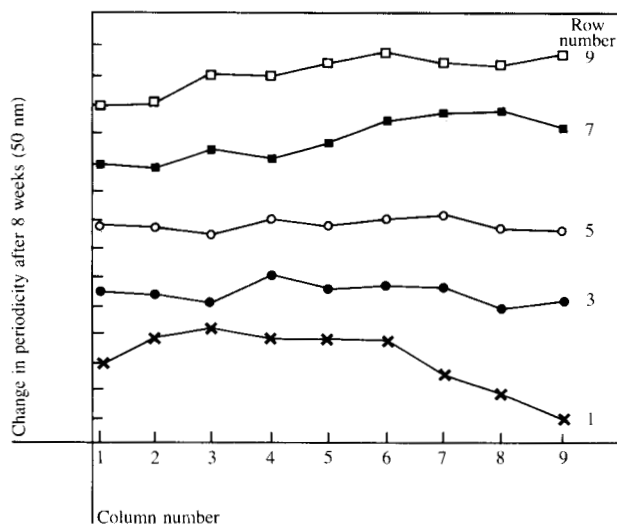


Figure 9 Two layers of patterns A and B were exposed onto the same substrate during an interval of eight weeks. The registration errors (for the x-direction) show a slight increase for rows 7 and 9, remain constant in the center, and decrease for row 1.

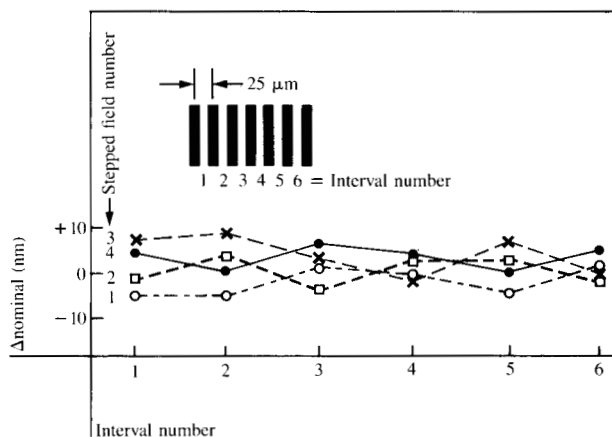


Figure 10 25- μm center-to-center distances between parallel 2.5- μm lines of four widely separated fields were measured and were found to remain practically constant.

ated a change in the 1 $\times$ field was the minute defocusing of the image plane by some 2–3 μm . Hence it seems reasonable to assume that the state of focus at the moment of exposure is critical, and sometimes it is not as accurately defined and repeatable as is generally believed.

Additional support for this assumption can be seen in Fig. 9, which illustrates the overlay of two pattern arrays which were exposed onto the same substrate about eight weeks apart [2]. This also minimized the influence of surface

flatness variations between plates. In each exposed field the spacing between the same two lines which are associated with the two overlaid arrays was measured. In the ideal case, all spacings should be identical for all fields, indicating a uniformity in mask stepping, as is to be expected from the laser-controlled tables. The measurements, however, indicate that the periodicity appears to change gradually from row to row, as shown by the changing tilt of the lines interconnecting the measurement points. Only the center rows displayed constant periodicity. The underlying cause of this somewhat unexpected behavior can be explained in terms of image-plane to optical-column biases and tolerances. For instance, the three reference planes which must be aligned and adjusted as accurately as possible (in some cases to within $\pm 1 \mu\text{m}$ per 10 mm) are the 10 $\times$ object plane, the lens flange, and the 1 $\times$ image plane. Additional problems arise from the uncertainty of accurate focusing during stepping (which can exceed 2 μm), inadequate focus setting (which is generally not optimized) and lens assemblage errors. (It appears unlikely that temperature effects and today's reliable interferometers could cause such short-term and systematic changes of periodicity.)

A theoretical effort was started to study the various causes of field size variations. Preliminary results indicate that asymmetries (such as coma, lens assemblage tolerances, incomplete pupil illumination) can cause asymmetric changes of the line intensity distributions. These, in combination with minute axial image plane changes, cause measurable changes of field size, in spite of telecentric designs.

In addition to the registration behavior along the periphery of the fields, one must also have some idea of what can happen on the inside of the fields. For this purpose, we measured the spacing of the same adjacent parallel lines (subfields) within various stepped fields, nominally 25 μm apart. As seen in Fig. 10, the optically generated subfields appear constant to within $\pm 0.01 \mu\text{m}$. Comparison studies of this nature, in conjunction with earlier results, and the high accuracy and precision in currently available automatic measurement systems permit the design of very sensitive and comprehensive product-inspection procedures and the identification of key efforts needed for system improvement. The factor which determines the performance of stepping systems to the greatest extent is the capability to maintain accurate focus over the entire field to within $\pm 1 \mu\text{m}$ at all times. The influence of the lens, the state of the camera adjustments, and the mask flatness may also seriously impair the performance of a system. The metrological techniques described in this paper can be used to determine factors of this nature very accurately and relatively easily.

It is difficult, and perhaps not worthwhile, to determine the accuracy of registration measurements between overlaid

arrays without going through a rigorous scientific study [4]. However, such effort is beyond the scope of this paper, which is limited to assisting the engineer in the manufacturing line to utilize available measurement systems expeditiously and to their maximum potential.

A more heuristic approach to assessing overlay measurement uncertainty of an automatic measurement microscope is facilitated by the intrinsic characteristics of the lithographic exposure systems. For instance, consider measuring the changes in periodicity of several rows of overlaid patterns and repeating the same measurement sequence over a long period of time. The degree of correlation between parallel sets of data points then permits statistical assessment of the measurement equipment bias and tolerances. It has been shown that the influence of measurement errors and coincidences can be reduced or even neglected if a satisfactory number of measurements are performed [5].

The degree of correlation can be seen in Figs. 8 and 10 and in particular in Fig. 4 of [2]. These results demonstrate that the degree of registration between overlaid arrays can be measured precisely to within $\pm 0.010 \mu\text{m}$. This is feasible for both axes. Similar measurement uncertainties for short-distance measurements were reported by Nyssonnen [6] and Jerke [7].

Two-dimensional measurement errors increase by a factor of 5 to 10 if a two-dimensional long-distance measurement system is utilized. The major errors here occur due to the uncertainty of controlling straightness of travel, plate clamping, environmental biases, and tolerances. Two-dimensional interferometer-controlled long-distance measurement systems have the advantage of automatic table movement between target sites. This type of system is preferable to use if many masks of the same type must be measured and if automatic data processing and printouts are required.

Conclusions

A major source of photomask misregistration has been determined by system monitoring over long periods of time. Uncontrollable changes of field size (exceeding $0.3 \mu\text{m}$) have been found. Uncertainty of focus can be shown to be responsible, but the real causes are unknown as yet. The problem is aggravated further by a variety of factors, such as adjustment tolerances of the optical components, mask waviness, inadequate setting of focus of the curved field, and lens assemblage errors.

Figure 11 summarizes the three types of field measurements used and reported in this paper. The application of special test patterns permits the accurate determination of individual variables of field registration of lithographic stepping systems and the inspection of product masks. Both types

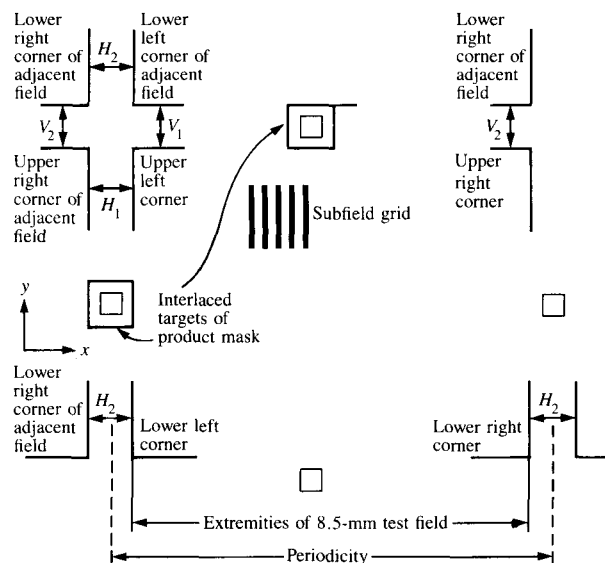


Figure 11 The location of the three types of test targets discussed in this paper in reference to the 8.5-mm-square field. Changes of all relevant pattern locations can be determined with a line width measurement microscope and yield information on variations in size, position, and orientation of fields (dies).

of measurements are performed routinely on the production line with a measurement uncertainty of $\pm 0.01 \mu\text{m}$ (1σ) and with relatively simple means.

While not explained here, generating mask sets within a short time interval (e.g., two to five days) generally provides masks of substantially better registration than those produced weeks apart. Another important observation is that different exposure systems of the same type appear to perform differently, some better than specified and some worse.

Finally, the objective for advanced microlithography exposure system design or improvement must be to reduce the major registration errors to within the range of the smallest random-type errors, which are equal to about $\pm 0.05 \mu\text{m}$ [2]. An important postulate pertaining to the concept of registration also seems to emerge from our results. It indicates that some dimensional errors cannot be measured by one set of measurements (at one point in time), however numerous and accurate they may be. Effective system characterization and determination of system performance can only be achieved by monitoring the factors and variables over long periods of time.

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